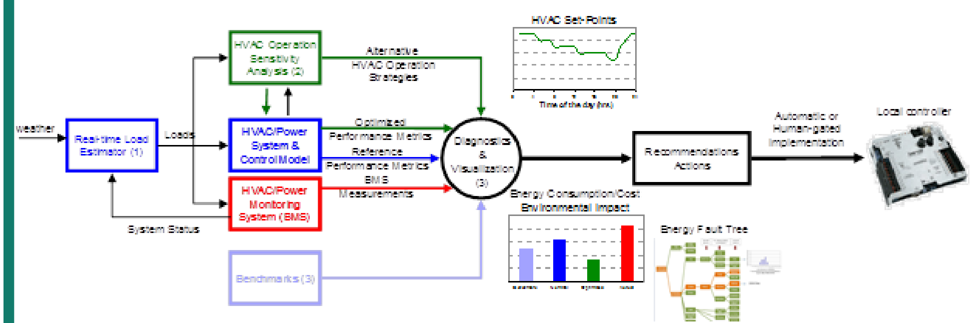
ESTCP
Cost and Performance Report

(EW-201015)



Scalable Deployment of Advanced Building Energy Management Systems

June 2013

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **Scalable Deployment of Advanced Building Energy Management Systems**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**48**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

COST & PERFORMANCE REPORT
Project: EW-201015

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

aBEMS	Advanced Building Energy Management System
AHU	Air Handling Unit
BACnet	Building Automation and Control Network
BDAS	Building Data Acquisition System
BEM	building energy model
BIM	building information modeling
BMS	building management system
DDC	direct digital control
DEM	a dehumidifier
DoD	U.S. Department of Defense
ECIP	Energy Conservation Investment Program
ESTCP	Environmental Security Technology Certification Program
FDD	fault detection and diagnosis
HVAC	heating, ventilation and air conditioning
kBtu	British Thermal Units
MILCON	Military Construction Correct
NIST	National Institute of Standards and Technology
ROM	reduced-order model
SERDP	Strategic Environmental Research and Development Program
SIR	savings to investment ratio
SPB	simple payback
USEPA	U.S. Environmental Protection Agency
UTRC	United Technologies Research Center
VAV	variable air volume

ACKNOWLEDGMENTS

This work was performed under the project EW-201015 administered by the Environmental Security Technology Certification Program (ESTCP) of the U.S. Department of Defense (DoD). We would also like to thank ESTCP Executive Director, Dr. Jeffrey Marqusee, the ESTCP Program Manager, Dr. James Galvin, and the Energy Manager at Naval Station Great Lakes, Mr. Peter Behrens, for their support.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The United Technologies Research Center (UTRC), with sponsorship from the U.S. Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP), has performed a demonstration of an advanced Building Energy Management System (aBEMS). The system employs advanced methods of whole-building performance monitoring combined with statistical learning methods and data analysis to enable identification of both gradual and discrete performance erosion and faults. The specific technical objectives of the demonstration project were to demonstrate: (1) 10% building energy savings by providing the facility engineers with actionable energy fault information to identify and correct poor system performance, and (2) an additional 10% energy savings by identifying alternative energy system operation strategies that improve building energy performance.

The demonstrated technology is targeted at commercial buildings that use building energy management systems. The demonstration was conducted in a drill hall/office building (Building 7230) and a large barracks facility (Building 7113/7114) at Naval Station Great Lakes. At Great Lakes, greater than 20% savings were demonstrated for building energy consumption by improving facility manager decision support to diagnose energy faults and prioritize alternative, energy-efficient operation strategies.

TECHNOLOGY DESCRIPTION

The aBEMS assimilated data from multiple sources including blueprints, reduced-order models (ROM) and measurements, and employed probabilistic graphical models and other advanced statistical learning algorithms to identify patterns of anomalies. The results were presented graphically in a manner understandable to a facility's manager. The system incorporated learning algorithms and simplified reduced-order simulation models to circumvent the need to manually construct and maintain a detailed building energy simulation model. This detailed building model is required for the existing technology (demonstrated in ESTCP project SI-0929) and represents a practical barrier to a broad scalable application. The facility Building Management System (BMS) was extended to incorporate the energy diagnostics and analysis algorithms, producing systematic identification of alternative, energy-efficient heating, ventilation, and air conditioning (HVAC) operation strategies. The scalability of the solution has also been demonstrated by applying (1) load estimation techniques and ROMs for the building and HVAC systems, reducing the need for constructing specific, detailed models for each building, and (2) probabilistic graphic models for energy diagnostics, as the graphic structure does not have to be learned for similar equipment and systems every time.

DEMONSTRATION RESULTS

The performance objectives were met during the demonstration as shown in Table 1. The overall performance evaluation for the aBEMS is summarized as follows:

- Greater than 20% savings was demonstrated for building energy consumption by improving facility manager decision support to diagnose energy faults and prioritize alternative, energy-efficient operation strategies.
- A ROM library for building envelope and HVAC equipment has been developed, validated, and tested by using demonstration buildings at Naval Station Great Lakes.
- A prototype toolkit to seamlessly and automatically transfer a Building Information Model (BIM) to a Building Energy Model (BEM) has been developed and tested. This dramatically reduced the time to create a BEM (50% time reduction).
- A tool chain for a scalable probabilistic graphical model-based energy diagnostics has been established, tested, and demonstrated. Greater than 15% energy savings was achieved by correcting air handling unit economizer faults. Greater than 95% of faults identified were classified correctly.
- A ROM based HVAC operation sensitivity study has been implemented and greater than 20% energy savings was identified by precooling/preheating the building, resetting chilled water supply temperature set points, resetting zone temperature set points, and optimizing outside airflow rate in the demonstration buildings.
- A visualization dashboard for building performance energy monitoring, HVAC operation strategies prioritization and energy diagnostics has been developed and deployed in demonstration buildings at Naval Station Great Lakes. This dashboard provides an effective way for building facility managers to perform building performance decision-making.

Faults and issues identified by the aBEMS were valued by the facility team because the tool provided additional visibility into the building operation that was not provided by the existing traditional BMS. This additional information allowed the facility team to identify previously unknown operational issues and prioritize their maintenance actions.

IMPLEMENATION ISSUES

The primary concern for the future implementation of the technology is the instrumentation cost. The largest components are the equipment and installation costs related to submetering and the on-site weather station. It is possible and reasonable to eliminate the on-site weather station by using weather data from the Internet or an existing weather station on the base. There is a need for additional research efforts to establish cost-effective submetering.

During the demonstration, the UTRC stage-gated technology and product development processes have been applied to begin transitioning the technology into a commercial product. The advanced building energy management system will be a part of a new BMS product or will be applied as an overlay on an existing BMS.

Table 1. Performance objectives results.

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
Quantitative Performance Objectives				
Reduce Building Energy Consumption (Energy) and Greenhouse Gas Emissions (carbon dioxide [CO_2])	Building total electric consumption (kilowatt hour per square foot per year [kWh/ft^2-yr]) and peak demand (kW) Building total steam consumption (therm/ft^2-yr) and peak demand Building total equivalent CO_2 emissions (kilograms [kg])	Metering data for building electric and steam usage Building simulation data for equivalent CO_2 emissions	>20% reduction in building total energy consumption (over baseline) >15% reduction in building peak demand energy (over baseline) >20% reduction in building total equivalent CO_2 emissions (over baseline)	>20% reduction in building total energy consumption (over baseline) 7~15% reduction in building peak demand energy (over baseline) >20% reduction in building total equivalent CO_2 emissions (over baseline)
Reduce Heating, Ventilation, and Air Conditioning (HVAC) Equipment Specific Energy Consumption (Energy)	Chiller (kW/ton) Cooling Tower (gallon per minute [gpm]/ton, kW/ton) Air handling unit (kW/ton) Fan (kW/cubic feet per minute) Pump (kW/gpm)	Submetering data for HVAC equipment	>10% reduction in HVAC equipment energy consumption (over baseline)	5 to 15% reduction in HVAC equipment energy consumption for air handling unit, fan (over baseline)
Reduce Building Loads (Energy)	Lighting loads (kWh) Plug loads (kWh)	Submetering data for lighting and plug loads	>10% reduction in lighting or plug loads (over baseline)	>20% reduction in lighting load (drill hall) with occupancy control
Building and HVAC System Reduced-Order Model (ROM) Validation	Building load (kWh) Building overall energy consumption (kWh/ft^2-yr) HVAC equipment energy consumption (kWh)	Simulation data from detailed building model (i.e., EnergyPlus) Metering data for building electric and steam usage Submetering data for lighting and plugs loads Building measured data	Predicted building loads difference (absolute error) between detailed model and ROM within +/- 10% Overall building energy consumption accuracy within +/-15% (ROM vs. measurement) HVAC equipment energy consumption accuracy within +/-10% at the rated conditions (ROM vs. measurement)	Predicted building loads difference (absolute error) between detailed model and ROM within +/- 10% Overall building energy consumption accuracy within +/-15% (ROM vs. measurement) HVAC equipment energy consumption accuracy within +/-10% at the rated conditions (ROM vs. measurement)
aBEMS Robustness	Percentage of faults classified correctly	Building energy fault identified/classified by aBEMS	85% of faults identified are classified correctly (during 3-month demonstration period)	>95% of faults identified are classified correctly

[1] Success criteria related to building and HVAC equipment energy consumption were assessed using both model-based simulations and actual energy measurements.

Table 1. Performance objectives results (continued).

Performance Objective	Metric	Data Requirements	Success Criteria[2]	Results
Quantitative Performance Objectives (continued)				
aBEMS Payback[3]	Simple payback (SPB) time Savings-to-Investment Ratio (SIR)	Cost to install and implement aBEMS Savings from using aBEMS	SPB time is less than 5 years[4] SIR is greater than 1.25	SPB time is less than 3 years SIR is greater than 2.5
Qualitative Performance Objectives				
Ease of Use	Ability of an energy manager and/or facility team skilled in the area of building energy modeling and control to use the technology	Feedback from the energy manager and/or facility team on usability of the technology and time required to learn and use	With some training, an energy manager and/or facility team skilled in HVAC able to use the aBEMS to identify and correct poor HVAC system performance	The user interface was refined based on feedback from facility team. The refined interface was well received.
Interactive and Visual Interface	Ability of an energy manager and/or facility team to effectively make building operation decision by using front-end user interface	Feedback from the energy manager and/or facility team on the interface	An energy manager and/or facility team able to more effectively exploit available building data to improve building operation decision-making	The user interface was refined based on feedback from facility team. The refined interface was well received.
Energy Fault Identification, Classification, and Prioritization	Ability to detect, classify and prioritize (based on energy impact) building faults	Building measured data Building simulation data	Energy manager and/or facility team able to detect, classify, and prioritize (based on energy impact) building faults by comparing simulated building performance (design intent or optimal) against measured building performance	The system flags faulty behavior via anomaly scores. This information enables facility team to prioritize faults based on energy impacts from simulation models.

[2] Success criteria related to building and HVAC equipment energy consumption were assessed using both model-based simulations and actual energy measurements.
[3] This payback success criterion is only applied to the case when the only retrofits considered are those that do not involve major equipment retrofits
[4] DoD Energy Manager's Handbook http://www.wbdg.org/ccb/DOD/DOD4/dodemhb.pdf

Performance Objective	Metric	Data Requirements	Success Criteria[5]	Results
Qualitative Performance Objectives (continued)				
Energy Fault Corrective Action Prioritization	Ability to prioritize energy fault corrective actions based on energy impact	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize energy fault corrective actions by comparing the simulated building energy impact benefits for each fault corrective action alternative against the simulated or measured baseline building energy performance	By comparing the simulated building energy impact benefits, the system enables facility team to prioritize the fault corrective action
HVAC System Operation Strategies Prioritization	Ability to prioritize the alternative energy-efficient HVAC system operation strategies	Building measured data Building simulation data	Energy manager and/or facility team able to prioritize energy-efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance	Energy manager and/or facility team able to prioritize energy-efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance
Scalability	Ability of aBEMS to be scaled to different types and sizes of buildings Time to implement the system for a new building	Feedback from the energy manager and/or facility team on scalability Implementation time for drill hall Implementation time for Building 7113/7114	Type of building: successful demonstrations for office and barracks buildings Size of building: scale from drill hall with smaller floor area to Building 7113/7114 with bigger floor area Implementation time is about 30% less for Building 7113/7114 compared with the drill hall	The aBEMS was successfully implemented in buildings with different types and different sizes (Building 7230: drill hall and office building with 70,000 sf^2 vs. Building 7113/7114: barracks building with 300,000 sf^2)

[5] Success criteria related to building and HVAC equipment energy consumption were assessed using both model-based simulations and actual energy measurements.

1.0 INTRODUCTION

1.1 BACKGROUND

The DoD is the largest single user of energy in the United States, representing 0.8% of the total U.S. energy consumed and 78% of the energy consumed by the federal government [1]. Approximately 25% of the DoD energy use is consumed by its buildings and facilities. The DoD currently has 316,238 buildings across 5429 sites, and in 2006 its facility energy bill was over $3.5B [2]. The Office of the Secretary of Defense published an energy policy to "ensure that the DoD infrastructure is secure, safe, reliable and efficient" [3], and subsequent energy policy is being guided by the Energy Policy Act of 2005, Executive Order 13423, and the Energy Independence and Security Act of 2007 to ensure a 30% energy reduction by 2015. Because of the large energy footprint of DoD facilities, increasing building energy efficiency offers the largest opportunity for reducing DoD energy consumption. Building HVAC systems consume greater than 30% of a building's energy consumption[6] and ensuring sustained, operational efficiencies of building HVAC systems is the focus of this demonstration project.

Studies show that building HVAC systems can consume greater than 20% more electrical energy than the design intent largely because of equipment performance degradation (e.g., filter or heat exchanger fouling), equipment failures, or detrimental interactions among subsystems such as cooling and then reheating of conditioned air [4]. Identifying the root causes of efficiency losses is challenging because gradual erosion of performance can be difficult to detect. Available technologies such as ENFORMA® Building Diagnostics[7] exist, but focus on detecting equipment level faults and must be programmed using rules. A key barrier is the lack of information at sufficient detail to isolate abnormal changes in load conditions or anomalous equipment operations. Although there has been considerable effort to develop and demonstrate advanced methods for building energy diagnostics and HVAC controls [5, 6, 7], the scalable realization of these methods has not been achieved.

To address these challenges in a scalable manner, the UTRC[8] performed a demonstration of a building energy management system that employs advanced methods of whole-building performance monitoring combined with statistical methods learning and data analysis to enable identification of both gradual and discrete performance erosion and faults. The system assimilated data collected from multiple sources including blueprints, reduced-order models (ROM), and measurements, and employed probabilistic graphical models and other advanced statistical learning algorithms to identify patterns of anomalies. The ROM is a simplified model derived from a high-dimensional physical model. The results were presented graphically in a manner understandable to a facility's manager. Importantly, the system incorporated learning algorithms and reduced-order simulation models to circumvent the need to manually construct and maintain a detailed building simulation model. This detailed building model is required for the existing technology (e.g., model-based real-time whole building energy performance monitoring and diagnostics demonstrated in ESTCP project SI-0929) and represents a practical barrier to a broad scalable application.

[6]Energy savings are based on 3.8 billion kWh per year of electricity consumed by DoD facilities in 2006 [1].
[7] www.archenergy.com
[8] www.utrc.utc.com

The demonstration was conducted in three buildings at the Naval Station Great Lakes. The facility BMSs were extended to incorporate the energy diagnostics and analysis algorithms, producing systematic identification of alternative, energy-efficient HVAC operation strategies. More than 20% energy savings for building energy consumption was demonstrated via the implementation of aBEMSs.

Expected Benefits: It is expected that the broad deployment of scalable building energy management systems that apply advanced energy diagnostics and alternative, energy-efficient HVAC operation strategies will deliver 20% savings for HVAC energy consumption at DoD facilities. With an annual DoD facility energy expenditure of $3.5B, a 20% energy savings would offer >$200M savings potential across all DoD facilities. Achievable annual energy savings amount to 0.8 billion kWh, which offer a reduction of 528,000 metric ton of CO_2 per year[9]. When the technology is commercialized, it is projected that the $200M DoD energy savings per year can be applied to the entire U.S. building stock and will result in approximately $5.3B energy savings per year.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this project is to demonstrate an aBEMS that enables facility managers to visualize building energy performance, diagnose building energy faults, and assess alternative, energy-efficient HVAC operation strategies. The demonstration was carried out at Naval Station Great Lakes, Illinois. This project demonstrated the scalability of the aBEMS to different types and sizes of buildings. This project delivered an aBEMS that enables facility managers to visualize building energy performance, diagnose building energy faults, and assess alternative HVAC operation strategies (Figure 1). The aBEMS was implemented as a software extension to the current existing Building Energy Management and Control System. For the Naval Station Great Lakes demonstration, this system interfaced directly with the Siemens Building Management System and resided on an independent computer. Before the demonstration, there was no HVAC equipment shakedown or testing.

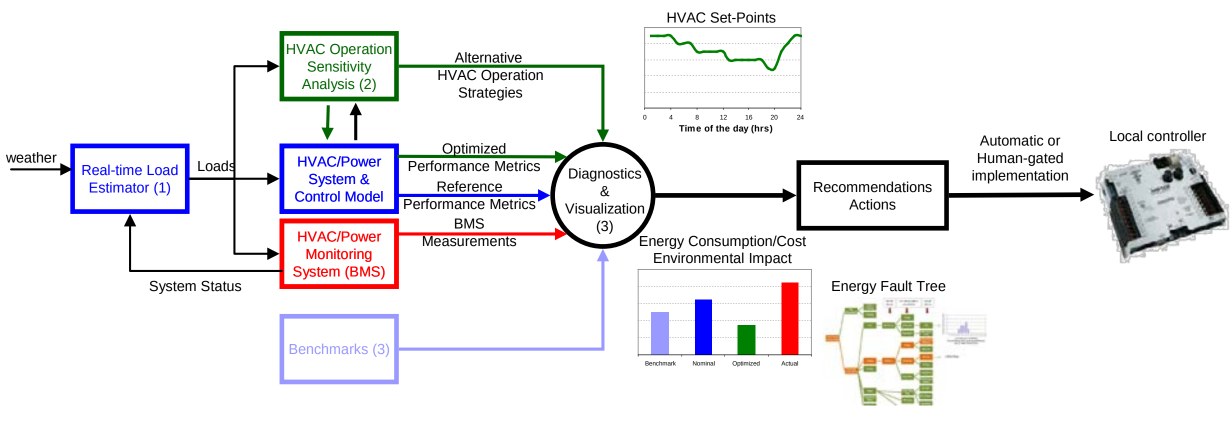

Figure1. Block diagram of the aBEMS.

[9] CO_2 emission reduction based on U.S. average of 1329 lb of CO_2/MWh of electricity generated (0.60 metric ton CO_2/MWh). http://www.epa.gov/cleanenergy/energy-resources/refs.html.

This project demonstrated the scalability of the aBEMS to different types and sizes of buildings. Specifically, the scalability of tools and methods for load estimation, ROMs for the building and HVAC systems, building and HVAC system energy diagnostics, building and HVAC system energy visualization, and HVAC operation sensitivity analysis were demonstrated.

The demonstrated technology is targeted at commercial buildings that use building energy management systems. The scalability of the solution was also demonstrated by applying (1) load estimation techniques and ROMs for the building and HVAC systems, thus reducing the need for constructing specific, detailed models for each building, and (2) probabilistic graphical models for energy diagnostics, where the graphical structure does not have to be learned for similar equipment and systems every time. The specific technical objectives of the demonstration project were as follows:

1. Demonstrate 10% building energy savings by providing the facility engineers with actionable energy fault information to identify and correct poor system performance, and
2. Demonstrate an additional 10% energy savings by identifying alternative energy system operation strategies that improve building energy performance.

1.3 REGULATORY DRIVERS

Executive Order 13423 [8], 13514 [9] and the Energy Independence and Security Act of 2007 (Title IV Subtitle C) require that U.S. federal agencies improve energy efficiency and reduce greenhouse gas emissions by 30% by 2015 relative to a 2003 baseline.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The demonstrated technology focused on the scalability of the aBEMS to different types and sizes of buildings. Specifically, the scalability of tools and methods for load estimation, reduced-order models for the building and HVAC systems, building and HVAC system energy diagnostics, building and HVAC system energy visualization, and HVAC operation sensitivity analysis were demonstrated. The project advanced and applied the following key technologies.

1. **Load Estimation.** A model-based estimation approach was used to provide information about unmeasured data relative to building energy performance (e.g., internal loads, infiltration, etc.). Estimation was performed using extended Kalman Filters [21], and was based on building ROMs.
2. **Reduced-Order Building and HVAC System Models.** Building envelope and HVAC system ROMs were used to predict system energy performance in buildings. Dynamic models are important to explicitly capture the nonlinear and dynamic energy performance in actual buildings (e.g., building envelope thermal mass for the storage). The dynamic coupling that exists between HVAC subsystems also requires models that consider dynamics (e.g., the slow dynamics from the building envelope versus the fast dynamics from the HVAC equipment; chiller, etc.). The building envelope and HVAC system ROMs, based on thermodynamics, thermo-fluid laws, and heat transfer analysis, were used for the following: (a) as a reference model to represent the "as-designed" building operation; (b) to estimate unmeasured variables and energy performance metrics; (c) to perform HVAC operation sensitivity analysis to evaluate the impact of various HVAC operation strategies on the building energy performance; and (d) to generate the ground truth data (i.e., the baseline) for data-driven energy diagnostics. The integrated ROM runs in the MATLAB [10] simulation environment
3. **Building and HVAC System Energy Diagnostics.** Building and HVAC system data represents a hierarchical structure of power usage and the delivered heating/cooling throughout the building. Identifying at which level in this hierarchy a fault-cause occurs is crucial to effectively provide facility management decision support. Building and HVAC system energy anomalies were detected and decision support methods were used to direct the facility manager to the likely root causes that were prioritized by the magnitude of the energy impact. To perform energy diagnostics, data mining and model-based estimation approaches were used to provide energy anomaly detection. A number of complementary modeling methods were used to implement energy diagnostic decision support. These include probabilistic graphical models [11, 12] and expert rule-based threshold methods [22].
4. **Energy Performance Visualization Tool.** The current state-of-the-art BMS provides facility managers with a rich set of building data. This building data includes system and equipment performance (temperature, pressure, energy consumption of building systems, etc.), controller status, and equipment fault status. However, the interconnected complexity and large volume of this building data often complicate

facility manager decision making. Today, facility managers rely on their personal intuition and experience to perform building operation decision making. This project developed an interactive, visual interface for facility managers to more effectively exploit available building data to improve building operation decision making. The energy performance visualization tool enables: (a) visualization of energy-related metrics at different building and HVAC systems levels; (b) decision support to enable the identification and prioritization of alternative, energy-efficient HVAC system operating strategies for facilities engineers; (c) energy fault diagnostics and root cause analysis; and (d) identifying persistent trends in energy usage. The energy performance visualization tool provided an interactive user interface for facility manager to access building energy operational data.

5. **HVAC Operation Sensitivity Analysis.** The current state-of-the-art BMSs do not readily provide facility managers with the capability to identify or prioritize alternative HVAC operation strategies that could deliver energy savings. Often, HVAC system energy improvement measures are down-selected for implementation without a rigorous assessment of the impact on the target building or HVAC system operation. The integration of the ROM for the building and HVAC systems with energy performance visualization offer an opportunity to rigorously assess energy impact of alternative HVAC operation strategies before and after implementation. HVAC operation sensitivity analysis methods were implemented within the energy performance visualization framework to allow the facility manager to identify and prioritize energy-efficient HVAC operation alternatives for implementation. Both single and simultaneous multivariable sensitivity analysis methods were implemented. As an example, single variable sensitivity analysis will allow the facility manager to assess if an increase or decrease in chiller supply water temperature set points will cause higher or lower system level energy consumption. A multivariable sensitivity analysis will allow the facility manager to identify more complex operation strategies that will lead to overall lower energy consumption. For example, one question is what direction and by how much should the chiller water supply temperature set point and fan speeds be modified when load conditions vary?

6. **Building Data Acquisition System (BDAS).** A BDAS was developed to acquire data from the BMS. The current version is able to acquire data from any Building Automation and Control Network (BACnet) protocol compatible system. In the future, this software may be expanded to cover other protocols. The current version is based on the Building Control Virtual Test Bed environment [13]. The following functions are supported by the BDAS system:

    - Gather data from systems that support BACnet protocol, and
    - Store data in a database.

7. **BIM to BEM Tool Kit.** A desirable building life cycle delivery process should include design, construction, commissioning and post-occupancy evaluation. It involves tremendous information storage and exchange. Although there are BIM-based design tools, such as Revit, to represent building data for design and there are currently no tools available to systematically translate building design data into building operational BEM. This lack of relevant tools results in a time-consuming and error-prone building energy modeling, and also impacts the results of model-based

fault detection and diagnosis (FDD). To address this issue, a BIM to BEM toolkit was developed. This toolkit includes a BIM-based database and automatically simulation code generation.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The broad, scalable application of building energy management systems that apply advanced methods for HVAC operational controls and energy diagnostics to DoD's facilities is a key for achieving the DoD's energy reduction targets. Ensuring that the energy management decisions made by DoD facility managers is based on a building monitoring system that raises the visibility of energy performance is key for delivering building energy savings.

The tangible DoD energy benefits are 20% savings for building energy consumption at DoD facilities where 10% is achieved through improved visibility of building energy diagnostics that provide facility engineers actionable data to identify and correct poor system performance and an additional 10% reduction achievable by providing HVAC set points that would optimize system performance. With an annual DoD facility energy expenditure of $3.5B and a 20% building energy reduction achieved through the application of energy-efficient operation strategies, the aBEMS would offer >$200M savings potential across all DoD facilities. Achievable annual energy savings amount to 0.8 billion kWh[10], which offers a reduction of 528,000 metric tons of CO_2 per year[11].

The intangible DoD benefits are to provide consistent energy management practices used by its facility managers through increased visibility into equipment performance, better informed decisions on maintenance and operational issues, improved forecasting of equipment life and equipment replacement and upgrade programs, and a reduction in emergency equipment failures. Ultimately, energy benchmarking and best-practice sharing across DoD facilities can also be achieved.

The advanced building energy management system differs from existing Energy Information Systems in the following ways:

- This system augments an existing BMS with additional sensors/meters and uses a ROM and diagnostic software to make performance deviations visible.
- Existing systems neither provide a viable means to quantify the value of a proposed HVAC operation strategy nor a methodology to quantify the value of different strategies. This system employs a physics-based ROM sensitivity study that is useful to estimate the economic value of different HVAC operation strategies. This actionable information will facilitate the facility manager's decision-making process.
- Compared to purely rule-based technologies such as Performance and Continuous Re-Commissioning Analysis Tool [14], this system uses a scalable physics-based ROM

[10] Energy savings are based on 3.8 billion kWh per year of electricity consumed by DoD facilities in 2006 [1].
[11] CO_2 emission reduction based on a U.S. average of 1329 lb of CO_2/MWh of electricity generated (0.60 metric ton CO_2/MWh). http://www.epa.gov/cleanenergy/energy-resources/refs.html.

together with data mining techniques such as probabilistic graphical network models for rigorous energy diagnosis.

- Existing systems do not provide a means to calculate and visualize the energy impact due to faults.

The technical risks and the corresponding mitigations are summarized as follows:

1. Model accuracy is crucial for model-based HVAC operation sensitivity studies. A load estimator was used to provide more realistic internal load input profiles to the model. Model calibration is very important and can be handled well by using auto-tuning tools [15].
2. The effectiveness and reliability of the data mining methods are directly related to the quality of the data collected (data gaps, inconsistent sensors, lack of full system information). Risk mitigation includes (a) supplementing the data with inputs derived by physics-based models, statistics and domain knowledge, and (b) sensor diagnostics.
3. The corrective actions to address faulty operation or other deficiencies identified by the tool may require modifications to building systems that are outside the scope of this contract or substantial capital expenditures that are beyond the means of this contract. Mitigation efforts were focusing on modifications to the control system that are realizable with minimal effort, and also on relatively simple fixes to the HVAC or lighting systems that fall within the expertise of the team and local facility staff.
4. The relatively high implementation cost is a major limitation. The largest components are the equipment and installation costs related to submetering and the on-site weather station. It is possible and reasonable to eliminate the on-site weather station by using weather data from the internet or an existing weather station on the base. To address this challenge, a low cost and scalable building energy monitoring system should be the focus of one of the future research efforts. This system should include the following:
    - A comprehensive design guideline to determine the minimum set of sensors for deploying energy monitoring systems in DoD buildings;
    - Virtual sensors derived from physical based models;
    - Low cost, scalable building electrical and thermal energy submetering;
    - Middleware that provides seamless data acquisition and automated point mapping into the advanced building energy management systems; and
    - Automated sensor health monitoring that combines heuristic rules, physics-based models, and data mining algorithms.
5. A deployment concern for this technology is the skill level required to install and maintain the system. A user manual and training for end users such as facility managers and building operators is necessary.

3.0 SITE/FACILITY DESCRIPTION

3.1 SITE/FACILITY LOCATION AND OPERATIONS, AND CONDITIONS

The first demonstration site was Building 7230, the Naval Atlantic Drill Hall, at Naval Training Center, Great Lakes, IL. Building 7230 is a two-story facility with a drill deck, office, and administrative rooms. The gross area of this building is approximately 69,218 ft^2. The second demonstration sites were Buildings 7113 and 7114 at Naval Training Center, Great lakes, IL. Building 7113 is a 149,875 ft^2 recruit barracks and is a long rectangular building, consisting of a large block of berthing compartments, heads (bathrooms), laundry rooms, classrooms, a quarterdeck with a two-story atrium and office spaces, and a large cafeteria/galley. Buildings 7113 and 7114 are functionally similar (include barracks, classroom, cafeteria, etc.) and share a common central chilled water plant.

3.1.1 Building 7230

The drill hall (Building 7230) HVAC system consists of four airside systems and two separate waterside systems. The drill deck is supplied by two variable-air volume (VAV) air handling units with heating and cooling capability. Operation of these units depends on the occupancy of the drill deck space. Double-walled sheet metal ductwork with a perforated liner and drum louvers distribute the air throughout the space. The office and administrative area is served by one VAV air handling unit with VAV terminal units (with hot water reheat). The classroom is served by one VAV air handling unit. The chilled water system consists of two 100-ton air-cooled rotary-screw type chillers with fixed-speed primary pumping and variable-speed secondary pumping. Heating is supplied from the existing basewide steam system through a steam-to-water heat exchanger. The hot water serves unit heaters, VAV box reheating coils, and air handling unit heating coils. There is an instantaneous stream-to-domestic hot water generator for domestic hot water service. The server room and communication service room are served by dedicated split systems.

3.1.2 Building 7113/7114

When Building 7113/7114 was occupied by recruits, it was occupied 24 hours a day for 7 days a week. Recruits spent about 85% of their time in the barracks. Recruits left the barracks for drills and marches and during personal time on Sunday and holidays. The HVAC equipment in Building 7113 is located in five mechanical rooms and an attic space. Building 7114 shares the absorption chillers, cooling tower, heating hot water heat exchangers, chilled water pumping system, heating hot water pumping system, and the condenser water pumping system with Building 7113.

A distributed Direct Digital Control (DDC) system, APOGEE™ Insight by Siemens Building Technologies is installed in Buildings 7230, 7113, and 7114. This system monitors all major lighting and environmental systems. Building electric meters are also read by the DDC system. Operator workstations provide graphics with real-time status for all DDC input and output connections.

The energy manager and facility team at Naval Station Great Lakes were willing to endorse and support the demonstration from the beginning of the exercise. The demonstrated aBEMS was implemented as an overlay on the existing BMS and had no direct interface with the HVAC equipment and system operation in the demonstration buildings. The aBEMS provided actionable information about building operation, such as HVAC system/equipment health status and fault priority list based on energy impacts, etc. Currently, the communication between the existing BMS and the aBEMS is one way, and building operators have the authority to take final actions based on the information provided by aBEMS.

3.2 SITE/FACILITY IMPLEMENTATION CRITERIA

The implementation of the aBEMS depends on the existing building control system communication capability. In general, the aBEMS can be applied to any commercial building with a BMS. It is desirable that the existing BMS in the building supports an open communication protocol such as BACnet, LonWorks, or Modbus. For the buildings that are not compatible with these open communication protocols, the BMS vendor can provide data drivers to make the building operational data available.

Another criterion for site selection is whether the building is undergoing a major renovation or has a renovation plan in the near future. The aBEMS is intended to apply to buildings that are operating in a relatively stable state.

Based on building stock information extracted from the DoD's real property asset database[12] and from Commercial Building Energy Consumption Survey[13] database, there are 31,461 buildings across the DoD with an area greater than 10,000 ft^2. It is likely that a BMS exists in these buildings and the demonstrated aBEMS will be applicable.

3.3 SITE-RELATED PERMITS AND REGULATIONS

- Regulation: None
- Environmental Permit: None
- Agreements: None

[12] The RPAD database contains a total of 216985 buildings.
[13] http://www.eia.gov/consumption/commercial/

4.0 TEST DESIGN AND ISSUE RESOLUTION

The technology was demonstrated in two phases at Naval Station Great Lakes.

Phase 1 targeted a single building (Great Lakes Building 7230). Building 7230 is a Navy drill hall and represents buildings with large interior spaces. Integrated ROMs (building envelope and HVAC systems) were constructed and calibrated based on as-built drawings and other reference material. Building instrumentation was deployed and data was collected. Tasks included energy diagnostics and decision support methods, energy visualization tool, and HVAC operation sensitivity analysis methods. The demonstration for Building 7230 was conducted from July 1, 2010 to March 31, 2011.

Phase 2 demonstrated the scalability of the proposed approach, and expanded the capabilities developed for a single building to a building campus at Naval Station Great Lakes (Buildings 7113, 7114, 7230). The scalability issues addressed in Phase 2 considered demonstration across buildings of different and similar types. Building 7113 represents a multifunction building that includes barracks, classroom, and cafeteria that is functionally different from Building 7230. Buildings 7113 and 7114 are functionally similar (include barracks, classroom, cafeteria, etc.) and share common central chilled water plant and were also used to demonstrate the scalability to buildings of different size. The objective for Phase 2 was to demonstrate the scalability of the advanced energy management systems to a campus level at Naval Station Great Lakes. Scalability addressed how ROMs and estimation methods for building and HVAC systems and the energy diagnostics, visualization, and HVAC operation sensitivity analysis can be reused.

Additional metering is required to calibrate models and accurately measure energy consumption to validate results. For Building 7230, the existing instrumentation system from ESTCP project SI-0929 [16] was used with additional measurements (i.e., chilled water British thermal unit [Btu] meters at the air handling unit local level). Details about the additional instrumentation for Building 7113/7114 can be found in Section 4.3 in the final report. The measurement accuracy of the submetering for electricity and thermal energy refers to Specifications Guide for Performance Monitoring Systems [19].

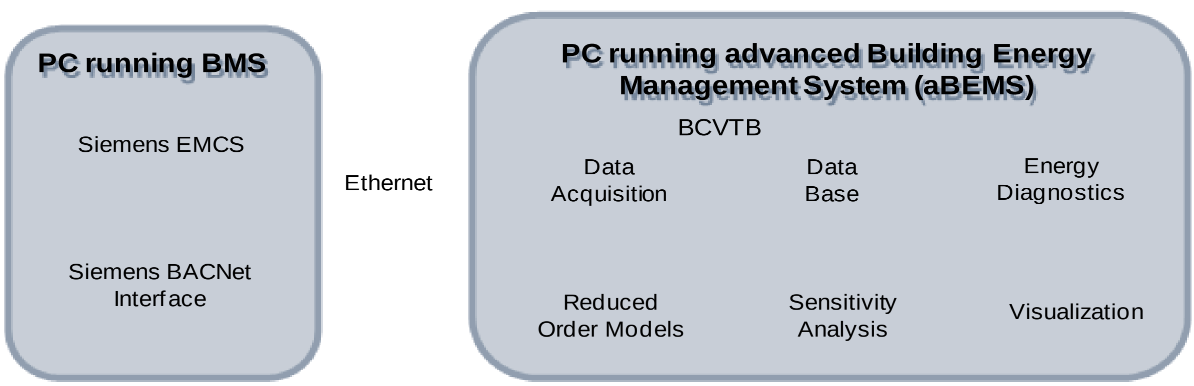

Figure 2. aBEMS diagram.

The schematic diagram for an online implementation of the aBEMS is shown on Figure 2. The aBEMS was running as an application on a PC at Building 7113/7114 to automatically and/or semiautomatically invoke the different functional modules (Data Acquisition, Database, ROM, Energy Diagnostics, and Sensitivity Analysis). A visual user interface application was available on the PC desktop. This user interface application allowed the facility team to plot a comparison of building energy consumption data, the ROM output, and sensitivity analysis results. The user interface application also allowed the facility team to automatically identify what building performance metrics are anomalous and where corrective actions should be prioritized. Figure 3 shows the demonstration system in Building 7113/7114, which is located in the Building 7114 penthouse.

At the end of the demonstration, the aBEMS was left in place and turned over to the site facility management team.

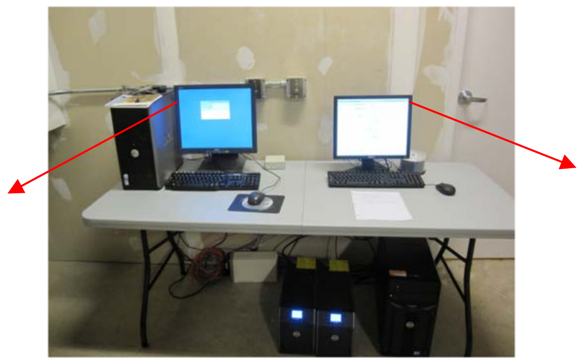

Figure 3. Demonstration system in Building 7113/7114.

5.0 PERFORMANCE RESULTS

5.1 SUMMARY OF PERFORMANCE OBJECTIVES AND OUTCOMES

Table 1 in Section 1 provides the summary for evaluating the performance of the aBEMS demonstrated at Naval Station Great Lakes.

5.2 PERFORMANCE RESULTS DISCUSSION

5.2.1 Quantitative Performance Objectives

1. *Reduce Building Energy Consumption (Energy) and Greenhouse Gas Emissions (CO_2).*

   Purpose: The ultimate goal of the aBEMS is to reduce energy consumption, peak electric demand, and greenhouse gas emissions in DoD facilities by providing actionable information to facility managers and building operators. This objective is to reduce building total energy consumption including HVAC, lighting, and equipment (i.e., plug loads).

   Analytical Methodology: Quantitative comparisons were performed between (1) measured data from current as-built building and the building with faults corrected and/or (2) predictions from different operation strategies based on a calibrated building ROM.

   Results: The following faults were detected and diagnosed at the demonstrated sites, Building 7230 (Drill Hall) and Building 7113/7114:

   - Economizer faults (Building 7113/7114);
   - Lighting faults (Building 7230); and
   - Absorption chiller issues (Building 7113/7114).

   As an example, Figure 4 below shows the measured chilled water consumption vs. outside air temperatures for July (with faults) and August (faults corrected) in Building 7114. The chilled water Btu meter measurement confirmed 18% chilled water consumption reduction as a result of the corrected economizer faults. Details for the energy faults diagnostics and savings calculations can be found in Appendices A.4 and A.5 in the final report.

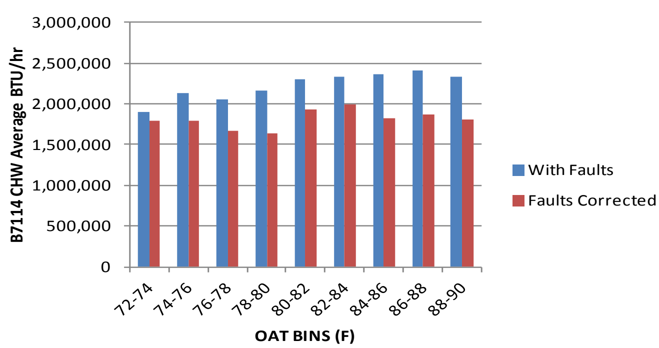

Figure 4. Measured chill water consumption comparisons (with faults vs. faults corrected).

The following HVAC operation strategies were evaluated using the integrated ROM:

- Precooling and preheating (Building 7230);
- Chilled water supply temperature set point reset (Building 7230);
- Zone temperature set point reset (Building 7113/7114); and
- Out air fraction optimal control (Building 7113/7114).

Details for HVAC operation sensitivity study assessment can be found in Appendix A.3 in the final report. The summary of the identified savings and related payback for Building 7113/7114 is provided in Table 2. Details for the performance assessment in terms of savings calculations can be found in Appendix A.5 in the final report.

Table 2. Summary of selected savings opportunities for Building 7113/7114.

<table>
<tr><th>Selected energy savings strategies</th><th>Energy Savings (%) compared with current operation</th><th>Annual savings in $[a]</th><th>Simple payback[b]</th></tr>
<tr><td>Economizer faults (enthalpy calculation)</td><td>18% (chilled water consumption[c])</td><td>$12,950</td><td>No initial cost</td></tr>
<tr><td>Zone temperature daytime set point reset (from 70°F to 74°F) in the cooling season</td><td>16% (B7113)
18% (B7114)</td><td rowspan="4">$52,834[d]</td><td rowspan="4">No initial cost</td></tr>
<tr><td>Zone temperature daytime set point reset (from 72°F to 68°F) in the heating season</td><td>11% (B7113)
15% (B7114)</td></tr>
<tr><td>Zone temperature daytime set point reset together with outside air control in the cooling season</td><td>24% (B7113)
12% (B7114)</td></tr>
<tr><td>Zone temperature daytime set point reset together with outside air control in the heating season</td><td>23% (B7113)
39% (B7114)</td></tr>
</table>

a. Assume (1) $0.069 per kWh for the electricity; (2) $8.7 per MMBTU for the steam; (3) use of 2011 utility bill for the baseline energy consumption.
b. Only consider the capital cost required to implement these energy savings strategies.
c. Measured savings based on Btu meter data from July 2011 to August 2011.
d. Assume 20% HVAC-related energy savings (electricity and steam) at the campus level; the rationale is provided in Appendix A.5 in the final report.

2. *Reduce HVAC Equipment Specific Energy Consumption*.

Purpose: Energy consumption reduction was also evaluated at the HVAC equipment level.

Analytical Methodology: Quantitative comparisons were performed between (1) measured data from current as-built building and the building with faults corrected and/or (2) predictions from different operation strategies based on a calibrated building ROM.

Results: The HVAC operation sensitivity study shows that the air-cooled chiller performance was improved by 5 to 10% in the terms of kW/ton. Fan electricity consumption was reduced by 10 to 11%.

3. *Reduce Building Loads (Energy).*

Purpose: Reducing building loads (e.g., lighting or plug) is an effective way to reduce building demand energy.

Analytical Methodology: Quantitative comparisons were performed between predictions from different operation strategies based on a calibrated building ROM.

Results: Lights in Building 7230 were on during unoccupied hours. Based on a calibrated building model, the electricity consumption at the building level could be reduced by 23% if occupancy-based light control was implemented in Building 7230.

4. *Building & HVAC System ROM Validation.*

Purpose: One featured innovation from the aBEMS is that it employs an integrated ROM for a whole building. The performance generated by this physics-based reference model, which represents "design intent" or ideal performance, is compared with measured data from the building. The performance deviation will indicate suboptimal operation or faults. The ROM was also used for the HVAC operation sensitivity analysis. The data generated from the ROM was used as the baseline for the FDD module. One of the key elements in the aBEMS is the validation of the ROM.

Analytical Methodology: Quantitative comparisons were performed between (1) predictions from a detailed model (i.e., EnergyPlus model) and a ROM, and (2) measurements and predictions from a ROM.

Results: Extensive validation has been performed in terms of load predictions from the building envelope ROM, energy performance predictions from the HVAC equipment ROM, and the integrated system ROM. Appendices A.1 to A.2 in the final report provide detailed information for the validation results. In summary, the total building load comparisons show that the differences between measurements and predictions for the integrated ROM are within the ±15% target for the majority of time. The model prediction errors are outside the ±15% error band when there are low-load conditions. This situation is as expected because the HVAC ROM performance is degrading at nonrated conditions.

5. aBEMS Robustness.

Purpose: It is critical for the success of this project that the aBEMS should be able to identify and classify building faults correctly.

Analytical Methodology: To quantify the accuracy of the diagnostics algorithm, a dataset with known faults (*a priori*) is needed. The algorithms can be then applied to the dataset to quantify how many of the known faults were detected correctly.

Results: For a detected economizer fault of Building 7114 air handling unit 1 during March 1 through 31, 2012, greater than 95% of faults identified were classified correctly. Details for the robustness analysis can be found in Appendix A.4 in the final report.

6. *aBEMS Payback Time.*

Purpose: Simple payback (SPB) and savings to investment ratio (SIR) were used as metrics to assess the economic viability of the aBEMS.

Analytical Methodology: The Military Construction (MILCON) Energy Conservation Investment Program (ECIP) template in the National Institute of Standards and

Technology (NIST) Building Life-Cycle Cost program [20] was used to calculate the SPB and SIR for the aBEMS deployed at the demonstration sites.

Results: Tables 4 and 5 in Section 6 summarize the cost analysis results for the Building 7113/7114 demonstration. Details for this cost analysis can be found in Section 7 and Appendix B in the final report. In summary, with current initial costs of $150,129 and HVAC-related energy savings of 20%, the SPB for the aBEMS in Building 7113/7114 is 2.85 years and the SIR is 2.78.

5.2.2 Qualitative Performance Objectives

1. *Ease of Use.*

   Purpose: The aBEMS should be an easy-to-use tool with an interactive interface for building facility managers and operators. The potential users of this aBEMS tool include the building energy manager and/or facility team who are skilled in the area of building HVAC systems (e.g., building energy modeling and controls). With some training, they should able to use the aBEMS to identify and correct poor HVAC system performance

   Results: The feedback from Great Lakes facility team on the usability of the technology and time required to learn and operate the aBEMS system was used to help the project team to develop, evaluate, and refine the aBEMS. The refined interface was well received.

2. *Interactive and Visual Interface*.

   Purpose: The aBEMS should provide an interactive and visual interface for facility managers and building operators to assist them in making effective building operational decisions.

   Results: The feedback from these users on the interface was employed to help the project team develop, evaluate, and refine the interface. The user interface was refined based on feedback from Great Lakes facility team, and the refined interface was well received.

3. *Energy Fault Identification, Classification, and Prioritization*.

   Purpose: The aBEMS should be able to detect, classify, and prioritize building faults based on energy impact.

   Results: The aBEMS enabled the energy manager and/or facility team to detect, classify, and prioritize building energy system faults based on energy impact by comparing simulated building performance (design intent or optimal) against measured building performance. The aBEMS automatically identified whole building performance deviations from the reference ROM by using probabilistic graphical network models, cluster analysis, and domain expertise. This approach enabled root cause analysis of these deviations, and not only an identification of a predefined, rule-based, set of equipment faults. It also provided a means to prioritize the faults based on energy impact. The data required to evaluate this metric was obtained from measurement and simulation.

4. *Energy Fault Corrective Action Prioritization.*

   Purpose: The aBEMS should be able to prioritize energy fault corrective actions based on energy impact.

   Results: The aBEMS enabled the energy manager and/or facility team to prioritize energy fault corrective actions by comparing the simulated building energy impact benefits for each fault corrective action against the simulated or measured baseline building energy performance. The physics-based, calibrated ROMs were used to evaluate the energy and economic value of alternative correction actions. The data required to evaluate this metric was obtained from measurements and simulation.

5. *HVAC System Operation Strategies Prioritization.*

   Purpose: The aBEM should be able to prioritize the alternative energy efficient HVAC system operation strategies.

   Results: The aBEMS enabled the energy manager and/or facility team to prioritize energy-efficient HVAC system operating strategies by comparing the simulated building energy impact benefits for each HVAC operation strategy against the simulated or measured baseline building energy performance. The data required to evaluate this metric was obtained from measurements and simulation.

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6.0 COST ASSESSMENT

A cost model for the advanced building energy management system is provided in Table 3. A detailed discussion can be found in Section 6 in the final report.

Table 3. Cost model for an energy efficiency technology.

Cost Element	Data Tracked During the Demonstration	Estimated Costs ($)
Hardware capital costs	Estimates made based on component costs for demonstration	$70,919
Installation costs	Labor and material required to install	$79,210
Consumables	Estimates based on rate of consumable use during the field demonstration	N/A
Facility operational costs	Reduction in energy required vs. baseline data	N/A
Maintenance	• Frequency of required maintenance • Labor and material per maintenance action	1 day per year ($1,000)
Hardware lifetime	Estimate based on components degradation during demonstration	0
Operator training	Estimate of training costs	1 day ($1,000)

[1] Detailed list of materials and analytical costs provided in the final report
N/A = not applicable

6.1 COST DRIVERS

6.1.1 Hardware Capital Cost

The hardware capital costs are mainly attributed to the additional instrumentation, which is required to provide run-time model inputs, calibrate models, and perform energy performance diagnostics. The measurements related to run-time weather inputs are as follows:

- Outdoor dry bulb temperature,
- Outdoor relative humidity,
- Direct normal solar radiation,
- Diffuse solar radiation, and
- Wind speed and direction.

The additional measurements required to track key performance metrics are electrical power submetering and thermal energy consumption for cooling and heating. The submetering of the electrical power should be able to measure the whole building electrical power and separate the lighting electrical power, plug load electrical power, key HVAC equipment (e.g., chiller), and total HVAC equipment electrical power. The detailed breakdown instrumentation costs for materials and labor are listed in Section 6.1 in the final report.

6.1.2 Solution for Weather Station

Real time weather data from an on-site weather station, including solar radiation data, are essential to reduce model prediction error. When deploying the technology, there are a few options that can be considered for cost reduction:

1. If internet access is available, the data from the National Oceanic and Atmospheric Administration website could be used directly without installing the weather station. If internet access is not available, as is the case at Naval Station Great Lakes, then a weather station has to be installed to access real-time weather data.
2. Multiple buildings on one campus are able to share one weather station with the necessary network setup to reduce the cost per building.

Building 7113/7114 is only about 100 feet away from Building 7230, which has an on-site weather station installed (ESTCP EW-0929). Unfortunately, the BMS networks from these two buildings cannot communicate with each other as a result of a Navy Information Technology security policy. To reduce the cost, a wireless subnetwork was created to acquire and transfer the weather information directly from the existing weather station in Building 7230 to the BMS network in Building 7113/7114. Table 6.4 in the final report compares the cost for two options. The total cost was reduced by more than 50% with a wireless solution.

6.1.3 Additional Sub-metering

The cost associated with the submetering is site-specific and presents the highest variable cost. The number of electric power meters needed to disaggregate depends on the layout of electrical circuits. The number of electric power meters needs to be determined by reviewing the electrical as-built drawings and through an on-site audit. The instrumentation for thermal energy measurement needs to be determined on a site-by-site basis.

6.1.4 Other Cost

A dedicated computer to host the software needed by the aBEMS is required. Most commercial available computers are adequate. A BACnet gateway is required only if the existing BMS is not BACnet compatible. Several site-specific characteristics that will significantly impact cost are highlighted here:

- **Networking capability for campus applications.** If networking is available to allow multibuilding sharing of a weather station, then only one weather station is needed.
- **Electrical system layout**. A good electrical system design requires significantly fewer electric power meters to disaggregate the end-uses.
- **Cooling and heating distribution system**. If long, straight main pipe segments are not available, then multiple Btu meters will need to be installed on the piping branches to obtain the total thermal energy consumption.

6.2 COST ANALYSIS AND COMPARISON

The MILCON ECIP template in the NIST Building Life-Cycle Cost program [17] is used to calculate the SPB and SIR for the aBEMS in Building 7113/7114. Section 5 and Appendices A.3, A.4, and A.5 in the final report provide details of savings opportunities from the demonstration buildings. It is assumed that there will be ~$1,000 savings per year per building

for operation and maintenance costs because the system downtime could be reduced and the facility team could better prioritize their work orders. The following assumptions are used:

- \$0.069/kWh for electricity and \$8.7/MMBTU for steam,
- No demand charge,
- Real discount rate of 3%,
- Inflation rate of 1.2%, and
- Length of study period is 10 years.

A few different capital cost scenarios (Table 4 for Building 7113/7114) were proposed after the analysis of the current capital cost structure. The assumptions used for different capital cost scenarios can be found in Section 6.2 in the final report.

Table 4. Different capital cost scenarios for Building 7113/7114.

Scenario 1 Full Capital Cost (\$ 150,129)	Scenario 2 87% of Capital Cost (\$ 130,537)	Scenario 3 76% of Capital Cost (\$ 114,657)	Scenario 4 57% of Capital Cost (\$ 85,244)
• BACnet server • 10 DEM • 8 Btu meters • 2 steam condensate meters • PC • Weather station (wireless solution)	• 10 DEM • 8 BTU meters • 2 steam condensate meter • Weather station (wireless solution) **Remove BACnet server and PC**	• 10 DEM • 8 Btu meters • 2 steam condensate meters **Remove BACnet server, PC and weather station**	• 10 low-cost electrical submeters • 8 Btu meters • 2 steam condensate meters **Remove BACnet server, PC and weather station** **Replace DEMs with new emerging sensors**

The SPB and SIR in different capital cost scenarios for the aBEMS demonstrated in the Great Lakes buildings are summarized in Table 5 below.

Table 5. Cost analysis results for Building 7113/7714 demonstration.

	Scenario 1 Capital cost	Scenario 2 87% of capital cost	Scenario 3 76% of capital cost	Scenario 4 57% of capital cost
First year savings:	\$52,734	\$52,734	\$52,734	\$52,734
SPB (in years):	2.85	2.48	2.17	1.62
SIR	2.78	3.20	3.64	4.9

Performance objectives were for less than 5 years for SPB and greater than 1.25 for SIR. As shown in Table 6.6, both objectives were achieved for the advanced building energy management system deployed in Building 7113/7114 including Scenario 1 (i.e., full capital cost as spent in this demonstration). The return on investment analysis depends on the baseline energy consumption for a given building. The energy usage index for Building 7113/7114 was 176.75 KBTU/sf^2-year in 2009.

Currently, some of the faults identified in Building7113/7714 are related to thermal comfort rather than energy consumption. For example, because of control/chiller problems, there were

times when the chiller was actually switched off when it was commanded on; therefore, the building consumed less energy than expected but the room temperatures were not maintained. The economic impact from occupant productivity as a result of lower thermal comfort is not quantified here as it is beyond the scope of this project. Based on an American Society of Heating, Refrigerating, and Air-Conditioning Engineers study [18] on the life cycle of a building, initial construction cost is about 2% and operational and energy cost is about 6%, while occupancy cost accounts for about 92%. The aBEMS is able to identify issues related to thermal comfort to help address productivity problems.

7.0 IMPLEMENTATION ISSUES

This section includes a discussion of the implementation issues in the areas of instrumentation, modeling, BMS integration, network communication, user interfaces and required skills issues.

7.1 INSTRUMENTATION

All the instrumentation is standard commercial off-the-shelf products. The recommended measurement accuracies for the power meters and thermal meters are given in *A Specifications Guide for Performance Monitoring Systems* [19]. A low-cost and scalable building energy monitoring system should be on the DoD demonstration agenda. This system should aim to reduce costs related to the energy monitoring systems necessary to enable aBEMS that integrates performance monitoring, energy diagnostics, and control technologies capable of delivering and maintaining 30% energy saving opportunities and reducing facility maintenance labor costs and improving occupant productivity. The following key technologies need to be addressed:

- A comprehensive design guideline to determine the minimum set of sensors for deploying energy monitoring systems in DoD buildings;
- Virtual sensors derived from physical based models;
- Low-cost, scalable building electrical and thermal energy submetering;
- Middleware that provides seamless data acquisition and automated point mapping into the aBEMS;
- Automated sensor health monitoring that combines heuristic rules, physical based models and data mining algorithms.

7.2 MODELING

Matlab was used in this project as the platform for simulation and visualization. For a technology demonstration project, the use of Matlab is appropriate. For broader deployment, existing Matlab code can be compiled and distributed as an executable program. In other words, the aBEMS can be deployed on computers without Matlab. The Matlab-based visualization is available only on the local machine (i.e., it is a “thick client”). The next generation system would use a web-based visualization tool. Also, information related to building current control sequences was not totally open because of a proprietary BMS on site. There is a need for a robust, scalable and standardized way to collect and store both static and operation dynamic data throughout a building life cycle.

7.3 BMS INTEGRATION

In this demonstration project, real-time building operational data was collected through a BACnet gateway by using the open source software, Building Control Virtual Test Bed [13]. A BIM supported database was prototyped and used to store both building static data (model parameters, HVAC configuration, etc.) and building dynamic operational data (e.g., temperature and energy). All the mapping was performed manually, which increased the implementation cost. It is recommended that the following activities should occur after this project:

- Extend a BACnet compatible data acquisition system to cover the other industry standard communication protocols.
- Develop a database structure that enables rapid mapping and use of both static building information and real-time dynamic operational data during the design and operational phases of a building life cycle. This structure should be tested in a variety of buildings with different types and sizes.
- Develop a services-based architecture to support the data exchange Application Programming Interface and computational services.

7.4 NETWORK COMMUNICATION

Significant challenges were encountered in the development and testing of the advanced building energy management system tool because of remote access problems. Network security constraints prevented this team from having remote access to the computers at Great Lakes. It is recommended that remote access be granted for developers implementing similar systems at other sites. This access should be in compliance with DoD Information Technology policy including Navy Public Service Network. Also, a secured and integrated DoD network should be established for building applications.

7.5 PERFORMANCE VISUALIZATION USER INTERFACE

The visualization interface has been refined and adapted based on feedback received from the facility team at the Great Lakes site. It is recommended that the following activities should occur after this project:

- Develop a flexible and extensible energy human machine interface that enables rapid development by common DoD facility users.
- Develop a standard mobile application for the proposed aBEMS. This step will make the recommendations provided by the proposed system immediately visible and actionable.

7.6 REQUIRED SKILLS

Using this aBEMS currently requires the installer to have the following skills: (1) ability to create a ROM model, (2) knowledge to set up the data acquisition system, and (3) knowledge to set up FDD models. Details for the ROM models, data acquisition system, and FDD models can be found in Appendices E, G, H, and I in the final report.

In summary, during the demonstration process at Naval Station Great Lakes, the maturity of the different technology elements have been assessed with gaps identified that will impact the successful deployment of a building energy performance monitoring and diagnostics system. After the completion of the Naval Station Great Lakes demonstration, it is recommended that the following list of activities should occur to ensure widespread technology deployment at the DoD.

1. Develop low cost and scalable building energy monitoring systems.

2. Implement a robust and scalable middleware for DoD buildings.
3. Deploy a secured DoD network for energy efficient buildings.
4. Integrate energy human machine interface applications for DoD building facility operations.

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8.0 TECHNOLOGY TRANSFER

8.1 COMMERCIALIZATION AND IMPLEMENTATION

During the demonstration, the UTRC stage-gated technology and product development processes have been applied to begin transitioning the technology into a commercial product. The aBEMS can be a part of a new BMS product or can be applied as an overlay on an existing BMS. To support a large-scale DoD deployment, UTRC has been engaging expertise from UTRC businesses:

- Automated Logic Corporation (ALC) – The demonstrated technology elements including BMS integration (middleware), energy diagnostics, and HVAC operation sensitivity analysis can be integrated into Automated Logic's WebCTRL BMS.
- NORESCO provides energy services to DoD facilities worldwide.

8.2 TRAINING REQUIREMENTS AND RESOURCES

Technical/Educational Sessions: The results of the technology demonstrated in this project have been or will be presented in the following events.

Journal and Conference Papers

1. O'Neill, Z., T. Bailey, B. Dong, D. Lou, and M. Shashanka. 2013. Advanced Building Energy Management Systems. *Annals of the New York Academy of Sciences.* DOI 10.1111/nyas.12188.
2. Dong, B., Z. O'Neill, D. Luo, and T. Bailey. 2013. Development and Calibration of a Reduced-order Energy Performance Model for a Mixed-use Building, *The 13th International Building Performance Simulation Association Conference and Exhibition*. Chambery, France. August 25–28, 2013.
3. Li, Z., B. Dong, Z. O'Neill, and G. Augenbroe. 2012. A Streamlined Workflow Process and Related Infrastructure for Building Fault Detection and Diagnostics. Submitted to *Automation in Construction.*
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End User Training: The team has provided user training to the facility team at Great Lakes. Three on-site demonstration and training sessions with the Great Lakes facility team were held in the demonstration building on September 12, 2011, January 12, 2012, and May 16, 2012. Figure 5 shows the training session on May 16, 2012. A training documentation was completed and will be available upon request from the ESTCP program office. The demonstrated aBEMS was introduced in the EPA Green Building Research Symposium on July 17, 2012, in Philadelphia, PA. The seminar was well received and the team was invited to submit a Journal paper to a special issue of *Annals of the New York Academy of Sciences* that discusses implications of a data-driven built environment. In the future, the team will attend specific conferences such as Strategic Environmental Research and Development Program (SERDP)/ESTCP Symposium and webinars such as Federal Energy Management Program's First Thursday's program to reach a broad government audience.

Figure 5. Training session in Naval Station Great Lakes on May 16, 2012.

8.3 DESIGN COMMUNITY IMPACTS

This project has identified a key remaining barrier for broader DoD deployment, which is the initial cost related to energy monitoring systems necessary to enable aBEMS. Currently, the DoD does not have a design guideline to determine the minimum set of sensors needed by energy monitoring systems (including electrical and thermal) for both new building design and existing building retrofit scenarios. A DoD building energy monitoring design guideline to determine the minimum set of sensors is needed. Existing reports [20] for building submetering systems should be incorporated and adapted. This design guideline should include a checklist of sensors and decision flowcharts that will help facilitate the deployment of advanced building energy management system across DoD facilities.

Recommendations that emerged from this demonstration that relate to building energy monitoring system, middleware, and a secured DoD network for energy efficient buildings should be integrated within the DoD Energy Manager's Handbook. The DoD should begin to publish guidelines and standards in the following areas to facilitate the deployment of aBEMSs across DoD buildings and facilities:

- A design guideline to determine the minimum set of sensors/meters required to deploy a comprehensive energy monitoring system for both new construction and retrofit of existing buildings; this guideline should include a checklist of sensors/meters and decision flowcharts for different HVAC systems;
- A guideline to establish a secured and integrated DoD network for building applications;
- A standard to share building energy usage data via a secured network using native communication protocols such as BACnet, Lonworks, etc.; and
- A standardized process to automatically collect building information from available references and transfer them to building energy applications such as BEMs.

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APPENDIX A

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